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INFORMAL REPORT

AIRBORNE TEMPERATURE SURVEYS
OF LAKE MICHIGAN,
OCTOBER 1966-OCTOBER 1967

MAY 1969

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INFORMAL REPORT

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ABSTRACT

Low-altitude surface water temperature mapping flights were carried out over Lake Michigan on 18 October 1966 and 25 October 1967, by the U. S. Naval Oceanographic Office Super Constellation, EL COYOTE, equipped with a Barnes Engineering Company Model 14-320 Airborne Radiation Thermometer. During the 1966 flight, a strong surface water thermal gradient ($4.4^{\circ}\text{C}/6000\text{ m}$) was observed to originate near-shore approximately one-third the way up the west shore of the lake, parallel the shoreline to approximately three-fifths of the distance up the lake, where it turned northeastward to the middle of the lake basin, where it again swung northward and became more diffuse. The surface thermal gradient was accompanied by a sharp visual color change, with the warm, green water to the east of the thermal gradient. Dynamic height currents computed from a BT transect through the gradient indicated a northward current (named the COYOTE CURRENT) of the order of 10-12 cm/sec in the gradient zone. The thermal structure persisted for a week. A similar temperature gradient - color separation - dynamic height current feature was observed paralleling the western shoreline during 1967. High Resolution Infrared Radiometer (HRIR) data from NIMBUS II meteorological satellite for 7 September and 6 October 1966, show a large, weak structure in the radiation temperature patterns that might be interpreted as precursors of the Coyote Current structure. It is suggested that this thermal structure might be a recurring seasonal characteristic of Lake Michigan.

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INTRODUCTION

This paper presents a summary of the results of flight programs carried out over Lake Michigan by the U. S. Naval Oceanographic Office in 1966 and 1967. High Resolution Infrared Radiometer (HRIR) data from NIMBUS II meteorological satellite were examined to confirm the prior existence of large-scale thermal features observed on the 1966 flights. The flight program was carried out by the NAVOCEANO Anti-Submarine Warfare Environmental Prediction Services (ASWEPS) as a pilot experiment over fresh water, both to demonstrate the capabilities of the airborne instrumentation as research facilities and to provide calibration information for the application of the instrumentation to other than completely marine environments. Also the mission was to demonstrate the potential of airborne oceanographic research on the Great Lakes and to make available, in public interest, Navy's advanced aerial oceanographic capabilities.

Full details of the 1966 flight have been presented in a special report by Noble (1967).

AIRBORNE MEASUREMENTS

During the 1966 program a Barnes Engineering Company Model 14-320 Infrared Airborne Radiation Thermometer (ART) was used to map the surface temperature of the lake on 23 east-west transects equally spaced over the lake's basin. In addition to the temperature measurements, opportunities were afforded during the week's operation to measure wave spectra with wave height radar, and to utilize several cameras and film combinations to investigate the applicability of cartographic cameras and Infrared Ektachrome, High-speed Ektachrome, Kodachrome, and Plus-X Pan Film.

The 1967 operation was limited by time and weather so that only surface temperature mapping was carried out. During both years of operation surface temperature calibrations were provided by ship support and BT transects were made across the lake basin along flight lines (in the south end and north end of the lake) to provide information on the three-dimensional temperature structure of the lake.

Figures 1a and 1b show the one minute average temperatures from the ART recording computed for points along the flight lines in 1966 and 1967 respectively. Figure 2 shows the surface temperature contours of the temperature distribution given by the one minute averages for 1966. The dramatic packing of the surface temperature isotherms along the west side of the lake extending from Milwaukee to Sheboygan, then turning northeastward to the center of the lake, was accompanied by a sharp color separation. To the east side of the

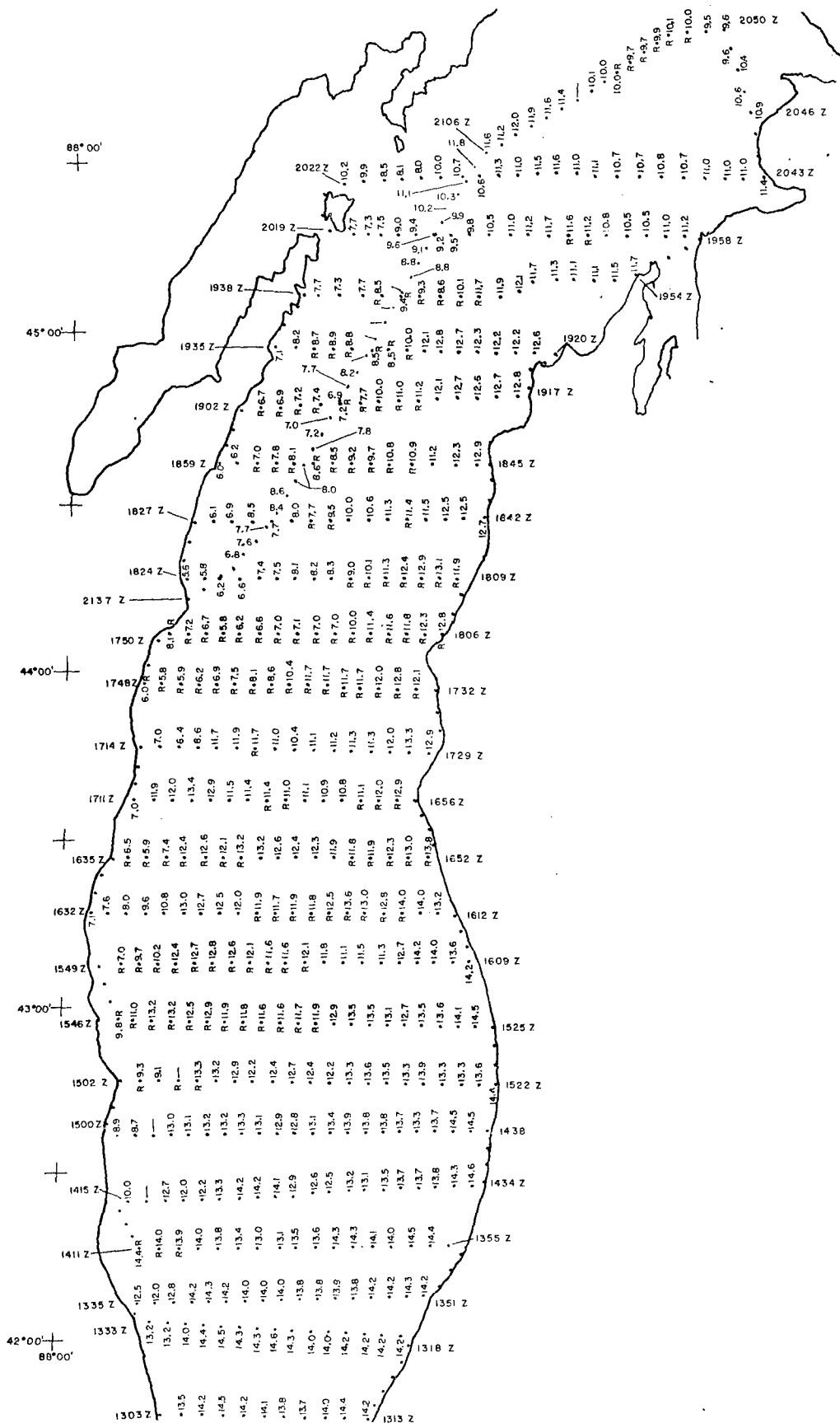


FIGURE 1a. FLIGHT PATH, LAKE MICHIGAN - 18 OCTOBER 1966,
SHOWING ONE-MINUTE AVERAGE AIR TEMPERATURES.

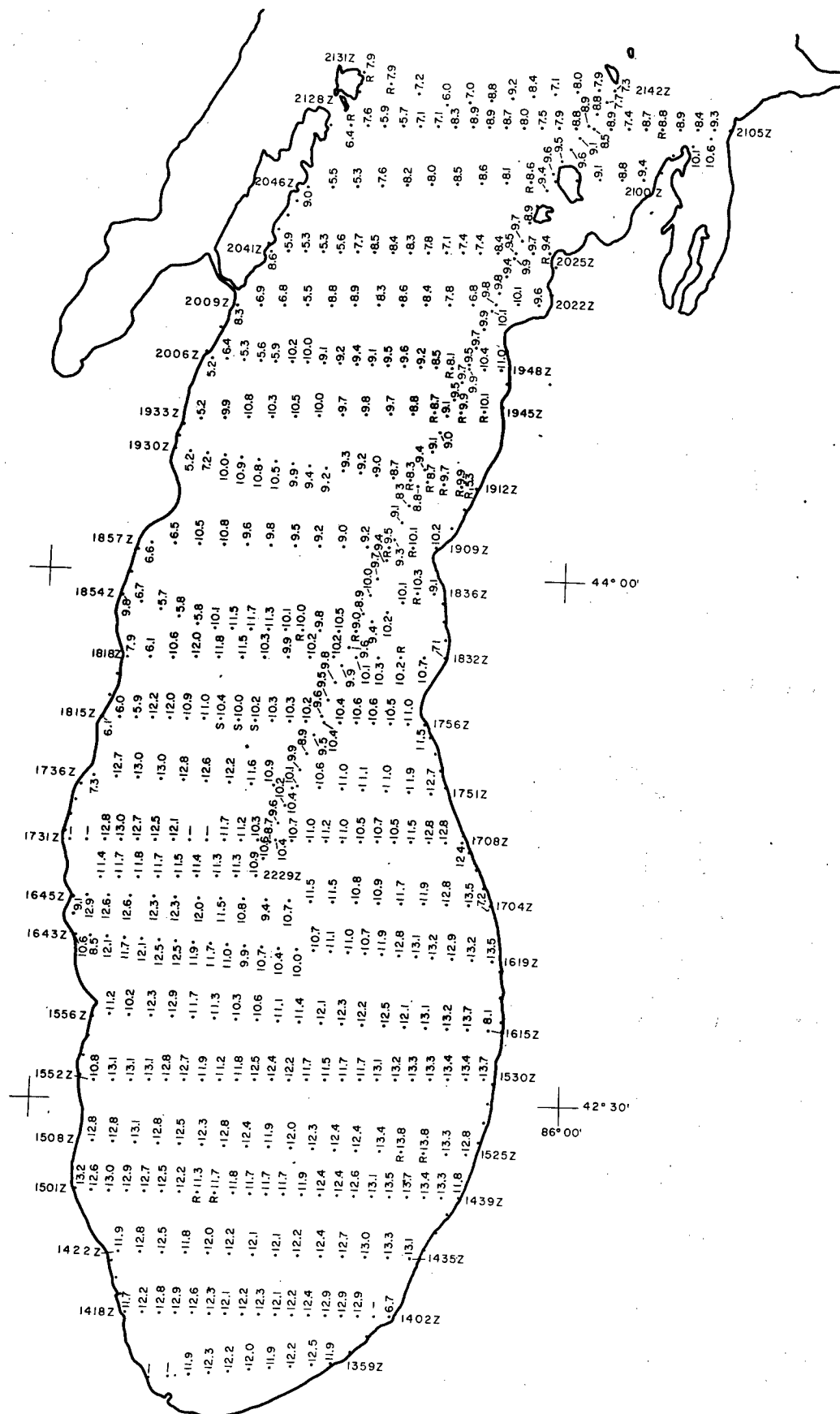


FIGURE 1b. FLIGHT PATH, LAKE MICHIGAN - 25 OCTOBER 1967, SHOWING ONE-MINUTE AVERAGE ART TEMPERATURES.

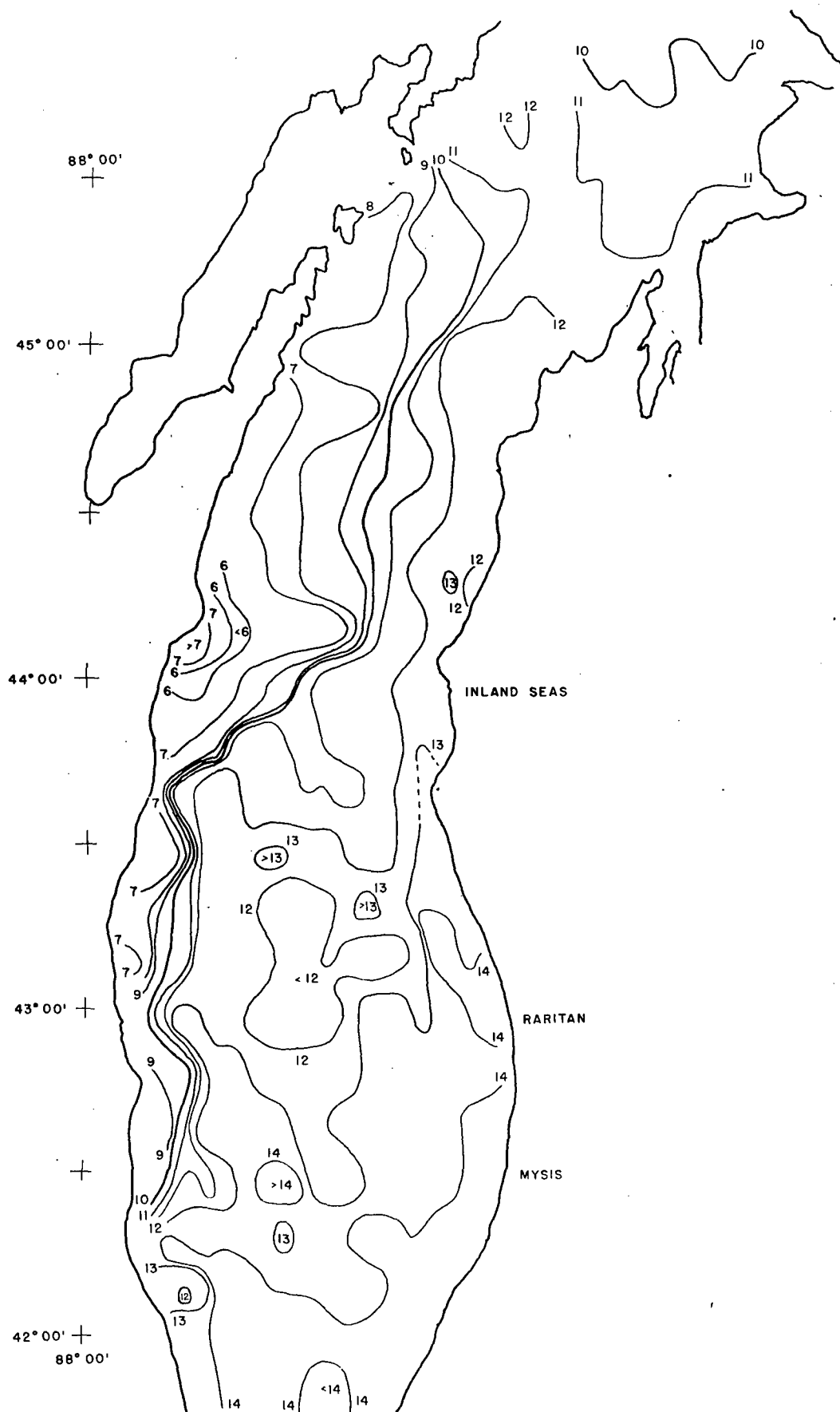


FIGURE 2. ISOTHERMS PLOTTED FROM ONE-MINUTE AVERAGE ART TEMPERATURES. LAKE MICHIGAN, 18 OCTOBER 1966.

thermal-front the surface water was warm and green. To the west side the water was cold and blue. Dynamic heights currents calculated from BT casts along the flight line of $43^{\circ}57.2'$ gave evidence of a strong current along the temperature gradient. At the end of the flight in 1966 this current was called the Coyote Current after the NAVOCEANO Super-Constellation EL COYOTE. The long flight mapping the surface temperature pattern was carried out on 18 October 1966. The Research Vessel INLAND SEAS transected the lake on the flight line, taking BT's at two-mile intervals across the lake basin on 18, 19 and 20 October 1966. No further mapping of the surface temperature structure was done after 18 October but subsequent flights showed that the general pattern persisted for the remainder of the week to the 21st of October. The temperature structure determined from the BT transects on 18 and 20 October 1966 along the $43^{\circ}57.2'$ flight line are shown in Figure 3. The temperature structure of the lake along a southern flight line $42^{\circ}26.5'$ was determined by BT transects from the Research Vessel MYSIS on 18, 19 and 20 October 1966. Figure 3 also shows the temperature structure along the $42^{\circ}26.5'$ flight line for 18 October 1966.

Following the observation of the surface temperature pattern and the accompanying Coyote Current in 1966, it was speculated as to whether this might be a recurrent seasonal feature of lake thermal budget and circulation patterns. Accordingly, through the winter, plans were laid for a similar flight to take place during October 1967.

The late summer-early fall period of 1967 was significantly cooler than that of 1966. Further, the flight operations in 1967 were scheduled for a date one week later than 1966. Finally, scheduling difficulties and bad weather prevented a series of flights such as had been carried out in 1966. The 1967 flight was therefore equivalent to being approximately two weeks later than that of 1966.

Figure 4 shows the surface temperature contours drawn from the one minute average ART records for 25 October 1967. Figure 5 shows the temperature structure of the lake determined from a BT transect carried out by the INLAND SEAS along a flight line of $43^{\circ}57.3'N$ and the temperature structure determined from a BT transect carried out from the MYSIS along the flight line at $42^{\circ}22'N$ on 26 October 1967.

The general surface temperature structure of the lake in 1967 was approximately $2^{\circ}C$ cooler than that of 1966. The west side temperature gradient was much sharper in 1967 than 1966, being of the order of $6^{\circ}C/4800$ meters at its sharpest point in 1967, and $4.4^{\circ}C/6000$ meters in 1966. A color separation along the thermal gradient existed similar to that of 1966. Figure 6 shows a

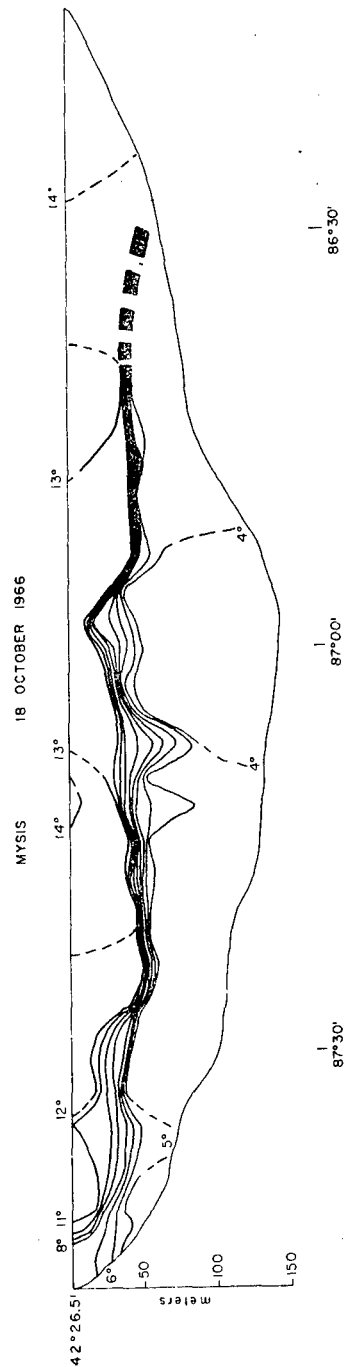
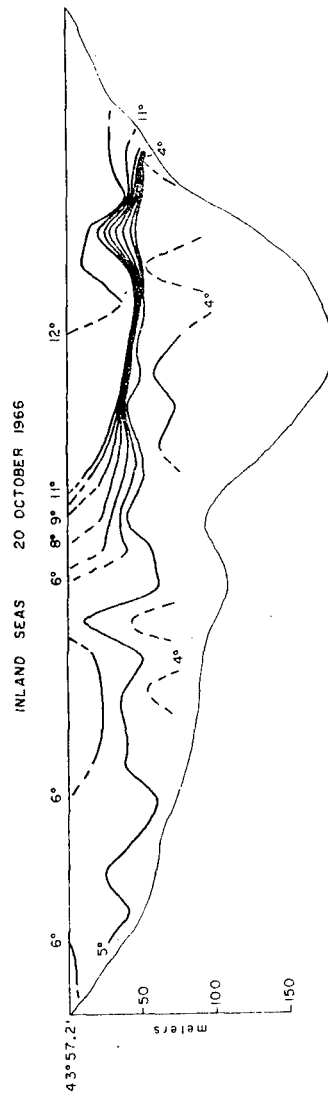
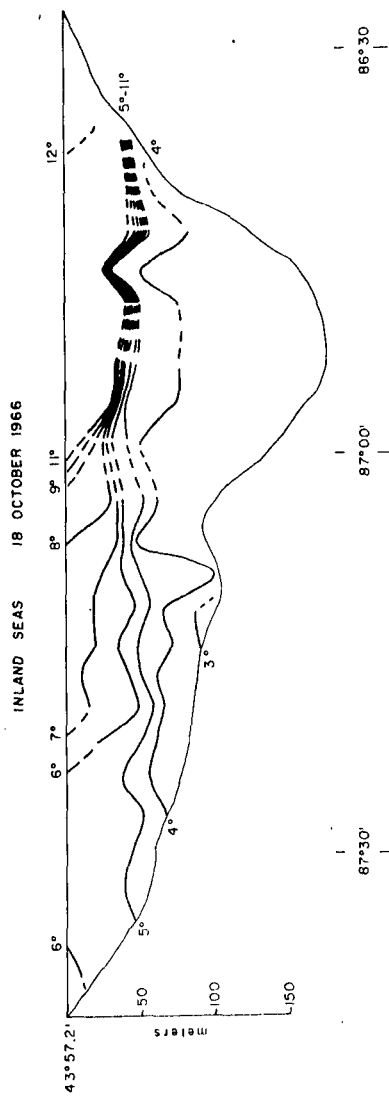


FIGURE 3. TEMPERATURE STRUCTURE OF LAKE MICHIGAN ALONG SECTIONS
43° 57.2' N AND 42° 26.5' N, 18 AND 20 OCTOBER 1966.

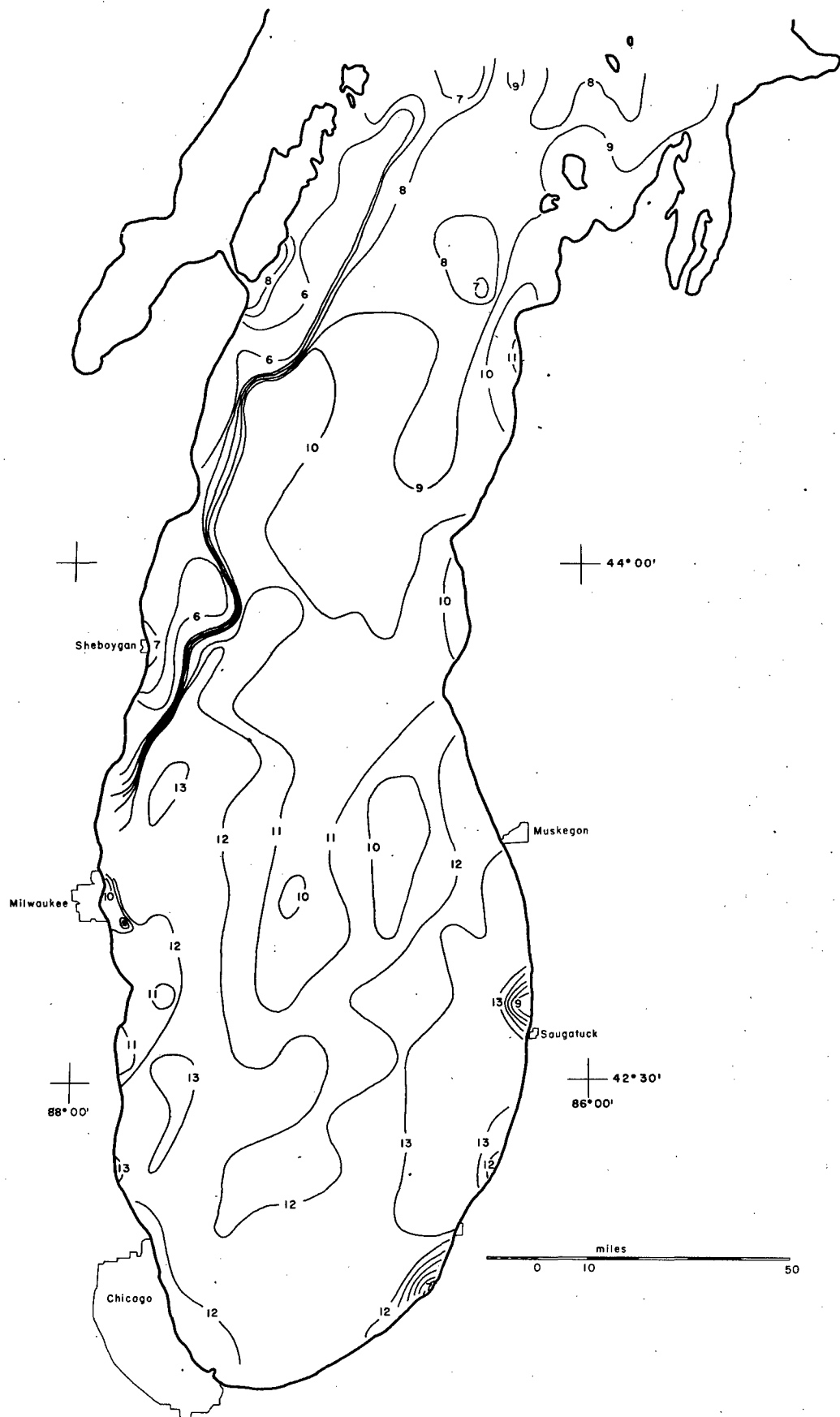


FIGURE 4. ISOTHERMS PLOTTED FROM ONE-MINUTE AVERAGE ART TEMPERATURES, LAKE MICHIGAN, 25 OCTOBER 1967.

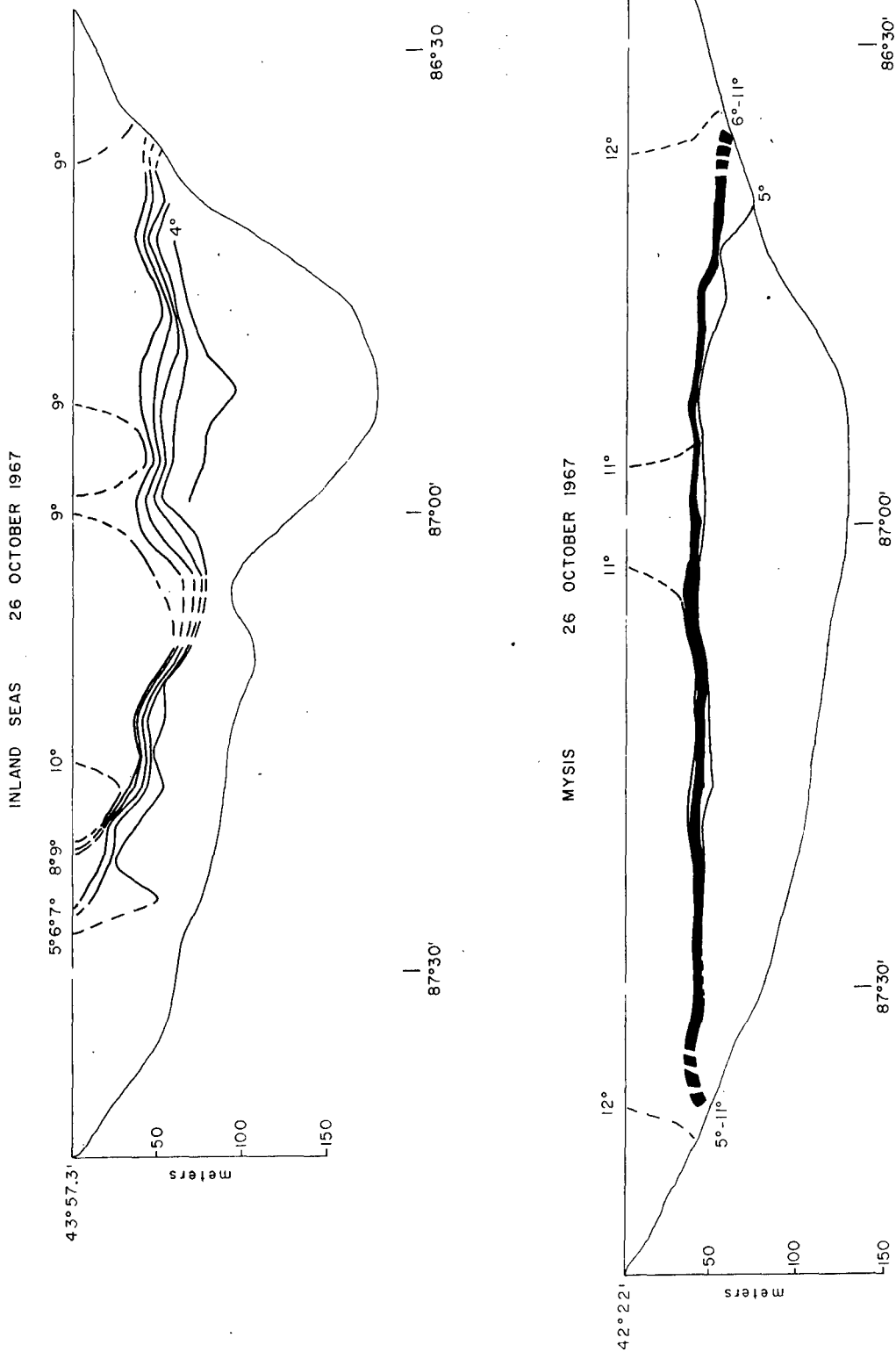
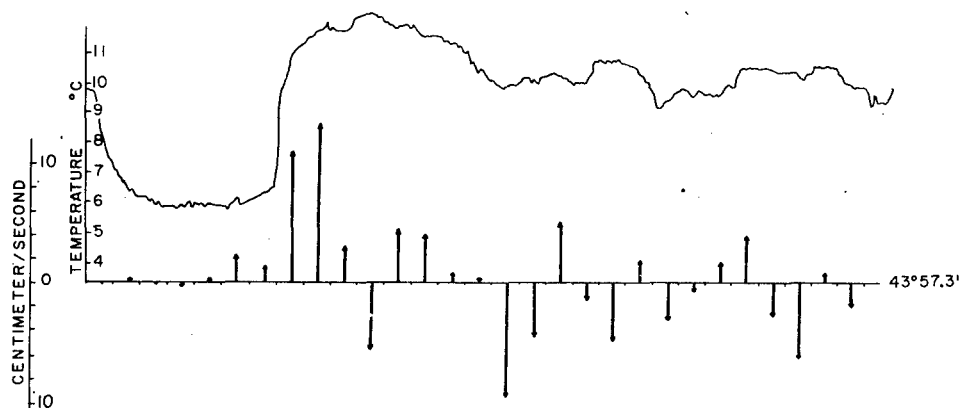


FIGURE 5. TEMPERATURE STRUCTURE OF LAKE MICHIGAN ALONG SECTIONS
 43° 57.3' N AND 42° 22.0' N, 26 OCTOBER 1967.



INLAND SEAS 26 OCTOBER 1967

FIGURE 6. SURFACE TEMPERATURE PATTERN AND 0-10 M LAYER DYNAMIC HEIGHT CURRENT COMPONENTS NORMAL TO THE CRUISE TRACK ALONG 43° 57.3' N, 26 OCTOBER 1967.

comparison between the surface temperature pattern and the 0-10m layer dynamic height current components calculated for the BT transect of 26 October 1967 carried out by the INLAND SEAS along the 43°57' flight line.

While the surface temperature structure observed in 1967 shows certain similarities to that of 1966, it is difficult to determine whether this phenomenon of a sharp temperature gradient accompanied by a current structure is in fact a recurrent or significant structure in the seasonal characteristics of Lake Michigan. After the 1966 flight it had been suggested that the temperature structure may have been the result of an upwelling. It does appear, however, that the 1966 phenomena is of too large a scale and too great a persistence to be described as the result of a simple upwelling. The 1967 structure being closer to the shoreline would more closely resemble that which would be expected from upwelling, however, the surface temperature profile shown in Figure 6 shows that the warmest surface water was encountered at the thermal gradient on the west side of the lake rather than finding the warmest water at the east shore as would be expected if the process were wind-generated upwelling.

CORRELATED SATELLITE DATA

In order to obtain an estimate of the build-up of the thermal feature documented as the Coyote Current during the week of 18-21 October, 1966, NIMBUS II meteorological Satellite data from September and October 1966 were examined to find thermal imagery of Lake Michigan preceding the Coyote flight that would permit comparable analysis of the surface temperature structure of the entire lake basin and provide confirmation of a prior existence of this dramatic thermal feature.

Two cases of nighttime, clear-sky, NIMBUS II, HRIR (3.5 to 4.1 μ) data were available for Lake Michigan preceding the ART flight of 1966. These were data orbits 1530 (7 September 1966) and 1916 (6 October 1966). The sub-satellite HRIR resolution element is 8.6 km by 9.7 km, with a sub-satellite point position error of approximately 1 degree of latitude and longitude. As the look angle of the scanner is swept through an arc transverse to the satellite track, the scan spot changes from rectangular at the sub-satellite point to an elongated trapezoid at larger look angles.

Digitized grid-print maps were obtained from Goddard Space Flight Center, NASA, for selected portions of data orbits 1530 and 1916 in which Lake Michigan appeared. In this data presentation, the elongated, over-lapping, resolution elements are averaged to yield a single digital value for the radiation temperature of the equivalent minimum resolution element (8.6 x 9.6 km) plotted on a rectified mercator projection. The mercator projection used in this study was a 1:500,000 scale.

Radiation temperatures contoured from the grid-print maps of Lake Michigan from orbits 1530 (7 September 1966) and 1916 (6 October 1966) are shown in Figures 7 and 8, respectively. For comparison, the geographic outline of Lake Michigan is shown in Figure 9. The cruise tracks of the car ferry CITY OF MADISON (between Milwaukee and Muskegon) and of R/V INLAND SEAS for 6 October 1966 (Mainistee to Kewaunee) are also shown on Figure 9.

The CITY OF MADISON made regular crossings of Lake Michigan between Milwaukee and Muskegon at 1330 and 0330. A recording thermograph was located in the MADISON's main sea chest, recording temperatures at an approximate depth of 12 feet. Figure 10 shows a comparison between the MADISON injection temperatures between 5 September and 9 September 1966, and the corresponding digitized radiation temperatures from the NIMBUS HRIR for 7 September 1966. Figure 11 compares the MADISON temperatures from 4 October through 7 October 1966 with the HRIR radiation temperatures of 6 October 1966.

Figure 12 compares injection temperatures from R/V INLAND SEAS (6 ft. depth) from the cruise track between Manistee and Kewaunee during the daytime of 6 October 1966 with the digitized grid print values from the NIMBUS orbit of the early morning of 6 October 1966. Note that the low grid-print temperatures near the shoreline at Manistee and the high values near Kewaunee reflect the averaging of up to four resolution elements to obtain a single grid-print value. (Due to the clear sky nighttime conditions, the radiation temperatures of the land mass are much colder than the water.)

Due to averaging of the resolution elements, problems in accurate positioning of the satellite, and of atmospheric absorption of the infrared radiation, comparison of the digital grid-print radiation temperature values with point surface temperature readings from ships, is difficult. However, large scale radiation temperature patterns have been shown to be meaningful in application to Lake Michigan research (Strong 1967).

The radiation temperature pattern of 7 September 1966, shown in Figure 7, shows a tongue of warm water trending northeastward from the west side of the lake at approximately 44°N. This tongue is delineated by the 290°K radiation temperature contour.

The radiation temperature pattern of 6 October 1966, Figure 8, shows a similar tongue delineated by the 284°K and 286°K temperature contours. In this case, the temperature contrasts are somewhat stronger than for 7 September 1966, and the tongue is more northward than for the previous case.

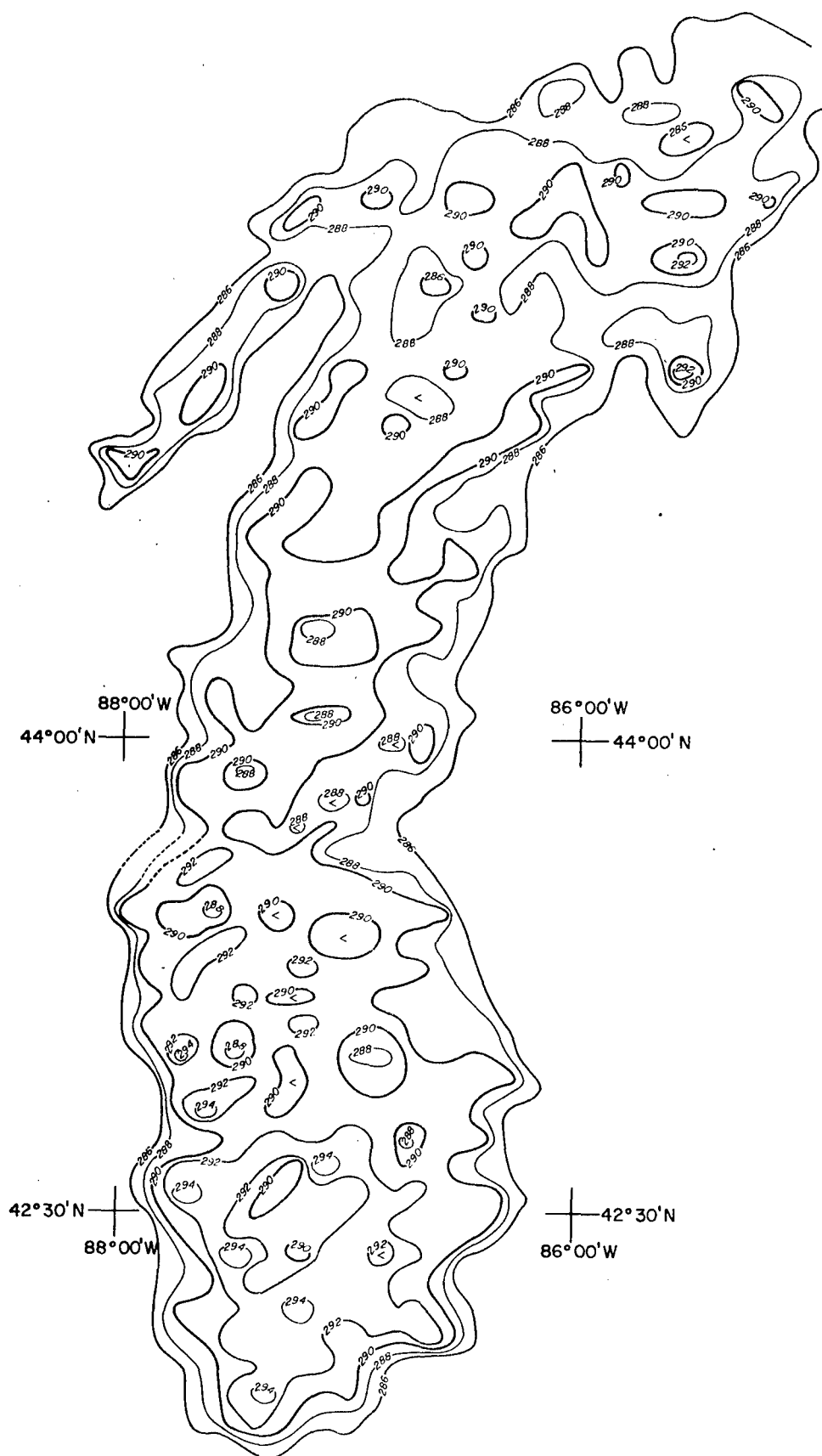


FIGURE 7. ISOTHERMS PLOTTED FROM DIGITAL GRID-PRINT MAP OF RADIATION TEMPERATURES FROM NIMBUS II HRIR SCANNER. DATA ORBIT 1530, 7 SEPTEMBER 1966.

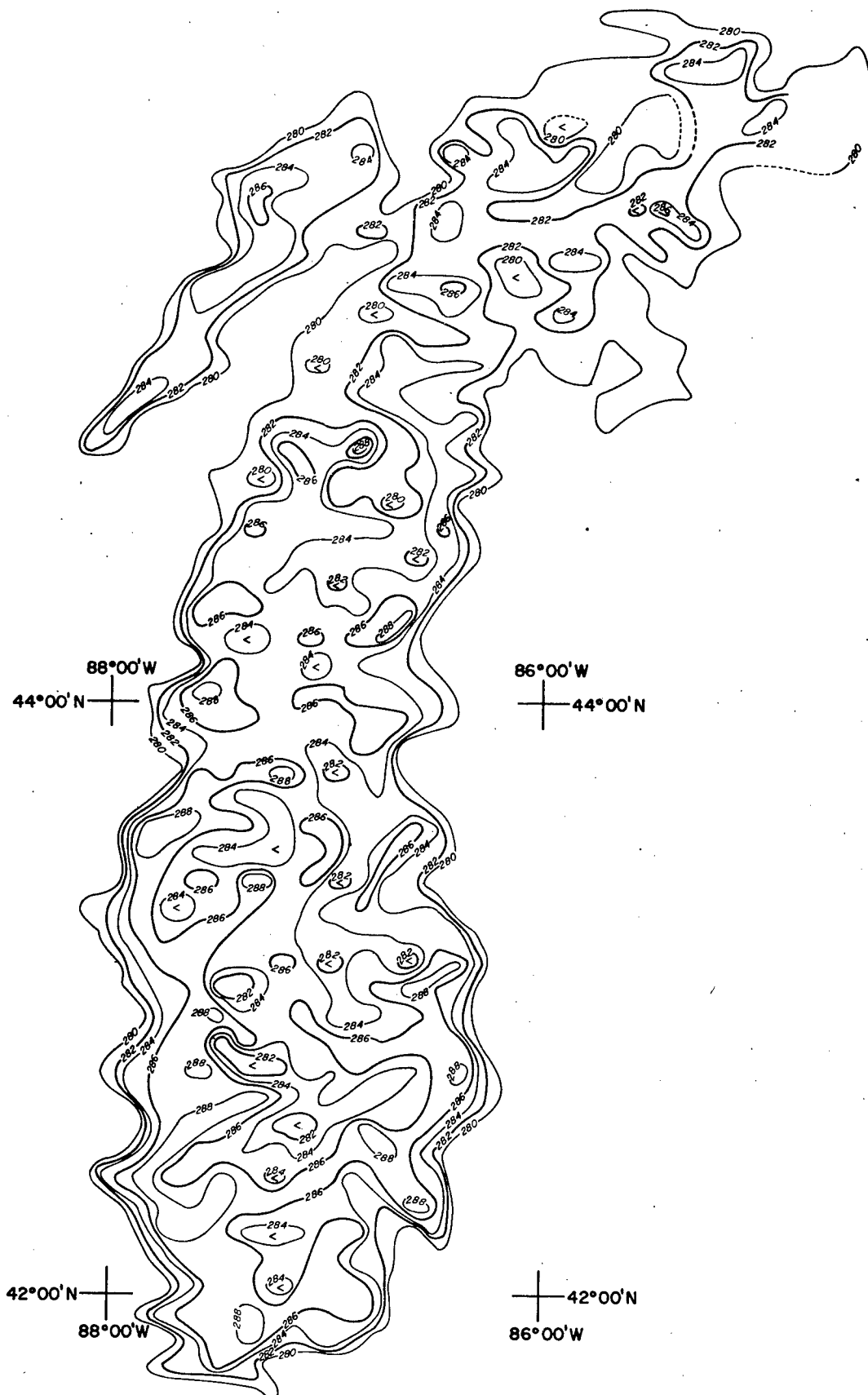


FIGURE 8. ISOTHERMS PLOTTED FROM DIGITAL GRID-PRINT MAP OF RADIATION TEMPERATURES FROM NIMBUS II HRIR SCANNER. DATA ORBIT 1916, 6 OCTOBER 1966.

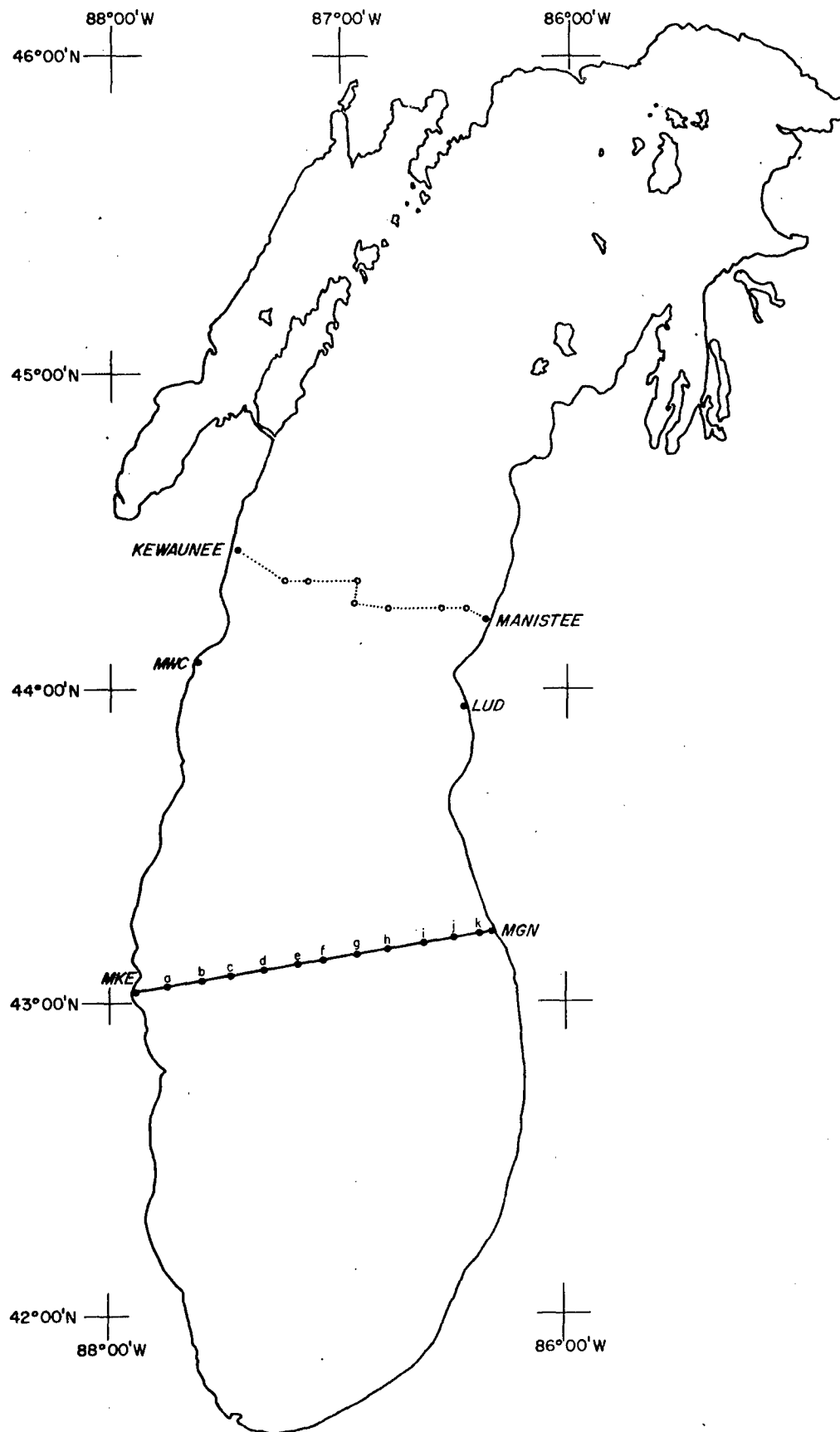


FIGURE 9. OUTLINE MAP OF LAKE MICHIGAN SHOWING MILWAUKEE-MUSKEGON CARFERRY ROUTE AND CRUISE TRACK OF R/V INLAND SEAS FROM MANISTEE TO KEWAUNEE - 6 OCT 1966.

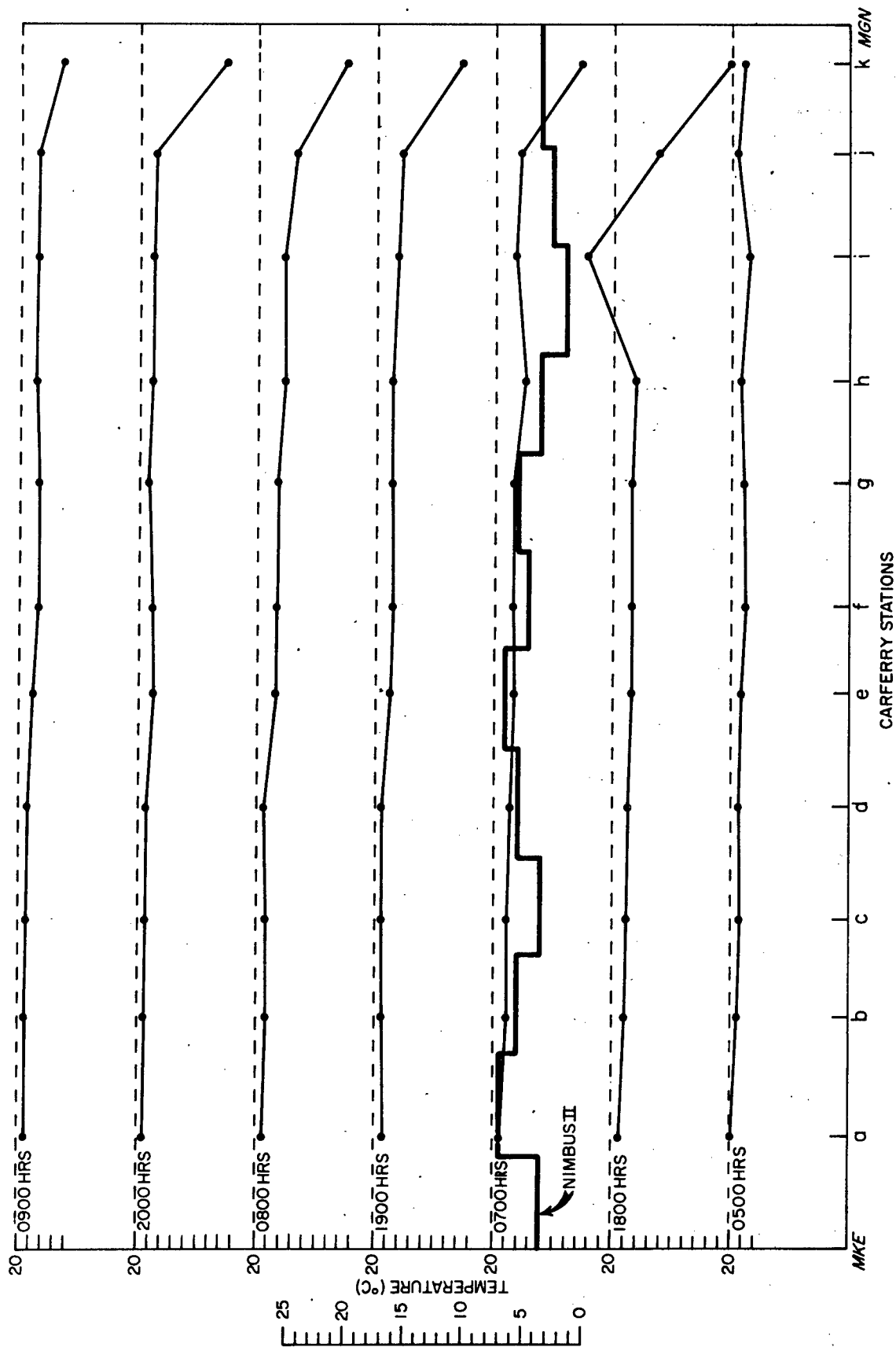


FIGURE 10. COMPARISON OF TEMPERATURE PROFILES ACROSS LAKE MICHIGAN FROM THERMOGRAPH RECORD OF INJECTION TEMPERATURES FROM CARFERRY CITY OF MADISON (5 SEPTEMBER 1966 THROUGH 9 SEPTEMBER 1966) AND DIGITAL RADIATION TEMPERATURE PROFILE FROM NIMBUS II HRIR GRID-PRINT MAP (7 SEPTEMBER 1966).

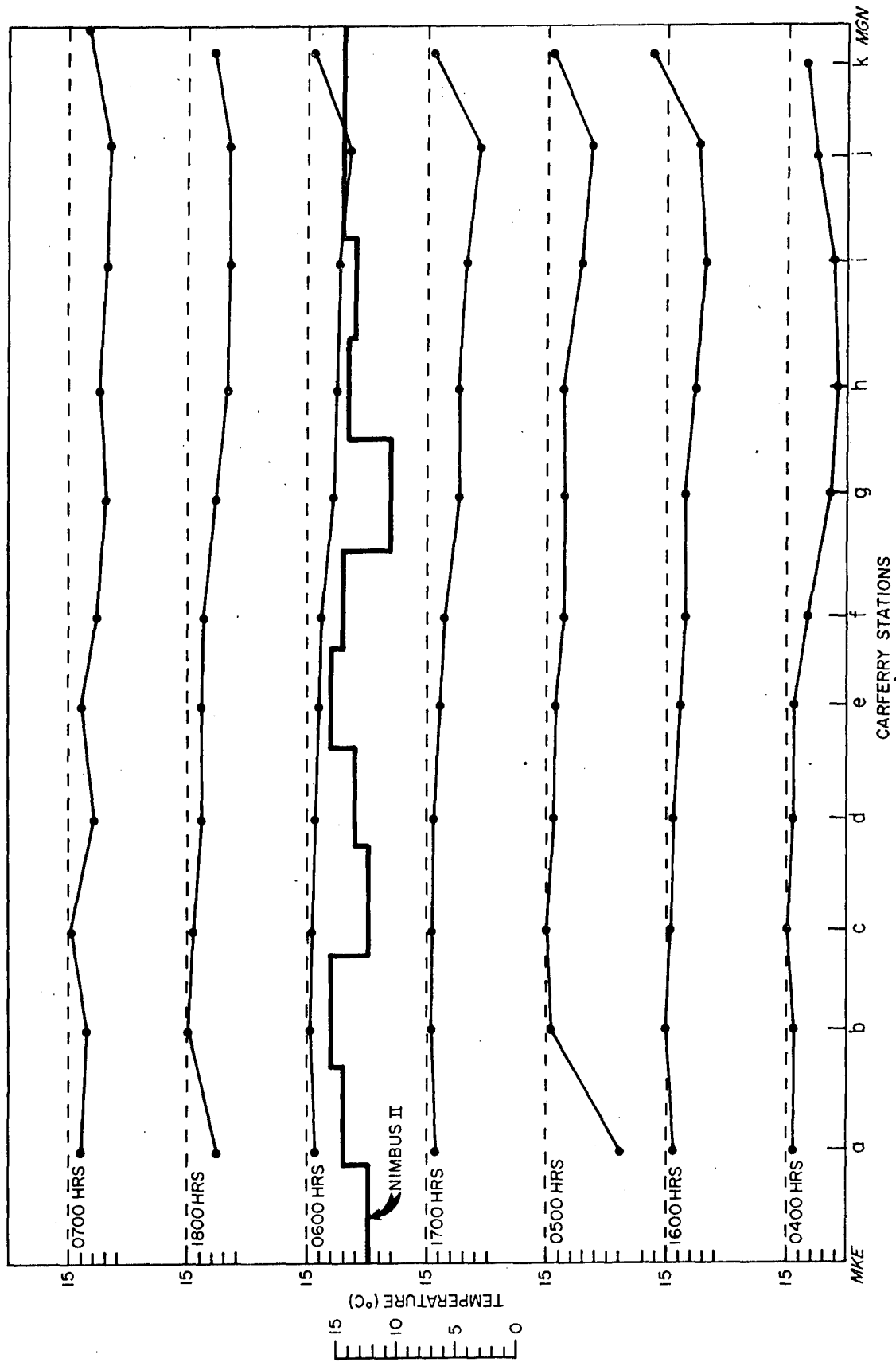


FIGURE 11. COMPARISON OF TEMPERATURE PROFILES ACROSS LAKE MICHIGAN FROM THERMOGRAPH RECORD OF INJECTION TEMPERATURES FROM CARFERRY CITY OF MADISON (4 OCTOBER 1966 THROUGH 7 OCTOBER 1966) AND DIGITAL RADIATION TEMPERATURE PROFILE FROM NIMBUS II HRIR GRID-PRINT MAP (6 OCTOBER 1966).

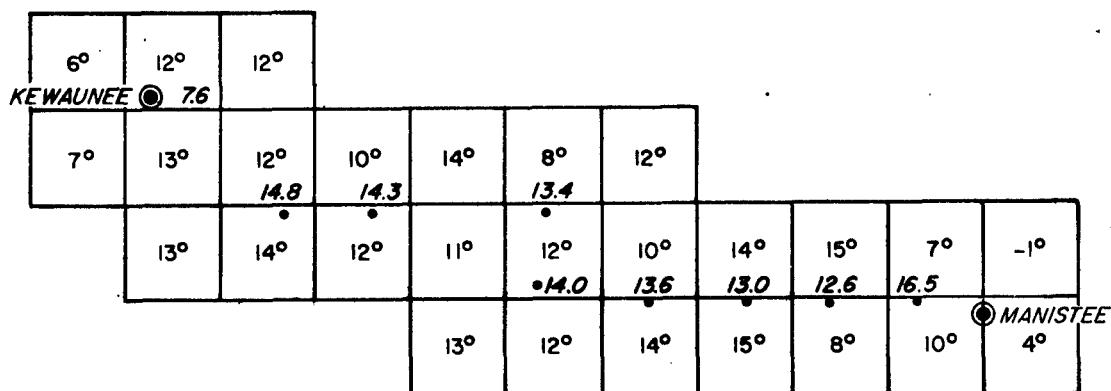


FIGURE 12. COMPARISON OF GRID-PRINT TEMPERATURE VALUES FROM NIMBUS II HRIR SCANNER (DATA ORBIT 1916, 6 OCTOBER 1966) WITH SURFACE TEMPERATURE READINGS FROM R/V INLAND SEAS (ALONG CRUISE TRACK FROM MANISTEE TO KEWAUNEE, 6 OCTOBER 1966).

It is suggested that this warmer tongue, that appeared in the NIMBUS HRIR radiation temperature data of 7 September 1966 and 6 October 1966, might be the precursor of the Coyote Current structure defined by the thermal mapping flight of 18 October 1966.

It is felt that the surface temperature structure of Lake Michigan should be monitored on a regular basis for another season with accompanying series of BT transects to determine the existence, persistence, and relation of the temperature gradient structure and Coyote Current structure to a regular seasonal characteristic of Lake Michigan.

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- Noble, V. E. (1967), Report of NAVOCEANO Flight Over Lake Michigan 17-21 October 1966. Spec. Rept. No. 31, Great Lakes Research Division, University of Michigan, Ann Arbor, 1967.
- Strong, A. E. (1967), The Overwater Development of a Lake Breeze in an Off-shore Gradient Flow. Proceedings, 10th Conference on Great Lakes Research. International Association for Great Lakes Research, 1967, pp 240-250.

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13. ABSTRACT

Low-altitude surface water temperature mapping flights were carried out over Lake Michigan on 18 October 1966 and 25 October 1967, by the U. S. Naval Oceanographic Office Super Constellation, EL COYOTE, equipped with a Barnes Engineering Company Model 14-320 Airborne Radiation Thermometer. During the 1966 flight, a strong surface water thermal gradient (4.4°C/6000m) was observed to originate near-shore approximately one-third the way up the west shore of the lake, parallel the shoreline to approximately three-fifths of the distance up the lake, where it turned northeastward to the middle of the lake basin, where it again swung northward and became more diffuse. The surface thermal gradient was accompanied by a sharp visual color change, with the warm, green water to the east of the thermal gradient. Dynamic height currents computed from a BT transect through the gradient indicated a northward current (named the COYOTE CURRENT) of the order of 10-12 cm/sec in the gradient zone. The thermal structure persisted for a week. A similar temperature gradient - color separation - dynamic height current feature was observed paralleling the western shoreline during 1967. High Resolution Infrared Radiometer (HRIR) data from NIMBUS II meteorological satellite for 7 September and 6 October 1966, show a large, weak structure in the radiation temperature patterns that might be interpreted as precursors of the Coyote Current structure. It is suggested that this thermal structure might be a recurring seasonal characteristic of Lake Michigan.

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